The Probable Optical Counterpart of the Luminous X-ray Source in NGC 6441[1]

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ABSTRACT

We report results from *Hubble Space Telescope* WFPC2 imaging of the field of the luminous, bursting X-ray source in the globular cluster NGC 6441. Although the X-ray position is known to a precision of a few arcseconds, this source is only $\sim 6''$ from the cluster center, and the field contains hundreds of stars within the $3''$ X-ray error circle, making it difficult to isolate the optical counterpart. Nevertheless, our multicolor images reveal a single, markedly UV-excess object with $m_{336} = 19.0$, $m_{439} = 19.3$, within the X-ray error circle. Correcting for substantial reddening and bandpass differences, we infer $B_0 = 18.1$, $(U - B)_0 = -1.0$, clearly an unusual star for a globular cluster.

Furthermore, we observe an ultraviolet intensity variation of 30% for this object over 0.5 hr, as well as an even greater variation in m_{439} between two *HST* observations taken approximately one year apart. The combination of considerable UV-excess and significant variability strongly favors this object as the optical counterpart to the low-mass X-ray binary X 1746–370.

With a group of five optical counterparts to high-luminosity globular cluster X-ray sources now known, we present a homogeneous set of *HST* photometry on these objects, and compare their optical properties with those of field low-mass X-ray binaries. The mean $(U - B)_0$ color of the cluster sources is identical to that of the field sources, and the mean M_{B_0} is similar to bursters in the field. However, the ratio of optical to X-ray flux of cluster sources seems to show a significantly larger dispersion than that of the field sources.

Subject headings: globular clusters: individual (NGC 6441) — stars: neutron — ultraviolet: stars — X-rays: bursts — X-rays: stars

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1. INTRODUCTION

For over two decades it has been known that globular cluster X-ray sources are overabundant with respect to those in the field (Katz 1975; Clark 1975). In fact, nearly 10^{-1} of the luminous X-ray sources ($L_X \gtrsim 10^{36}$ erg s^{-1}) in the Galaxy are found in clusters. The question of whether these cluster sources are somehow different in nature from sources in the field, or they are the same but the globular cluster environment enhances their formation probability, remains unanswered.

Thus far only four optical counterparts to globular cluster luminous X-ray sources are known: those in M 15, NGC 6712, and NGC 6624 seem secure, and a good candidate which still requires confirmation has recently been provided in NGC 1851 (Deutsch et al. 1996a). The difficulty in identifying optical counterparts is almost certainly primarily due to the extreme crowding in the clusters, which limits the utility of ground-based identification programs. All but the optically bright star AC 211 in M 15 have required the resolution of *HST* for confident identification. We have obtained multicolor *Hubble Space Telescope* images of several globular clusters containing X-ray sources, with the aim of resolving optical counterparts in crowded fields and studying their spectra, and report here on the results from WFPC2 images in NGC 6441. This paper extends the preliminary results and original counterpart identification suggested in Deutsch et al. (1996b).

The intense X-ray source in the core of NGC 6441, X 1746–370 (= 4U 1746–37), is a "classical", high X-ray luminosity ($L_X \sim 6 \times 10^{36}$ erg s^{-1}) burster observed for many years, by many satellites. However, it is distinguished by being one of the few cluster sources with a periodic X-ray modulation, exhibiting a 5.7 hr period of $\sim$ 5% amplitude (Parmar et al. 1989, Sansom et al. 1993). The source is located just $6''$ ($\sim 1\ r_c$) from the cluster center, and thus the optical field is very crowded. To our knowledge there has not even been a past suggestion of a candidate optical counterpart before this work, despite some effort (Bailyn et al. 1988). The small number of high luminosity cluster sources for which details are available already presents a confusing picture: despite similar X-ray luminosities, their optical luminosities and orbital periods differ by several orders of magnitude. The orbital period of this object is intermediate between the NGC 6624/6712 sources *vs.* M 15 AC 211.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Planetary Camera Imagery

On 1994 August 8, we obtained *HST* WFPC2 images centered on NGC 6441 through the F336W (50 s, 2 × 500 s) and F439W (50 s, 500 s) filters, similar to Johnson U and B, respectively. These frames are free of any artifacts or scattered light from the nearby bright star HR 6630 ($V \sim 3$) which often hinders observations of this cluster. The images have been processed through the standard data reduction pipeline at ST ScI. Further reduction was performed with software written in IDL by E.W.D. or available in the IDL Astronomy User's Library (Landsman 1993).

The sets of exposures were combined with a cosmic-ray rejection algorithm. We use DoPHOT (Schechter et al. 1993) to photometer stars in all four chips of the WFPC2. The PSF-fit magnitudes are calibrated using aperture photometry of isolated stars, where aperture corrections

are taken from Table 2(a) in Holtzman et al. (1995b). The photometric measurements have not been corrected for geometric distortions, nor is any correction for charge transfer efficiency losses (Holtzman et al. 1995b) applied, as there is sufficient charge on the chips to minimize this effect. We use the photometric zero points for the STMAG system from Table 9 (Z_{STMAG}) in Holtzman et al. (1995a). Systematic errors for all magnitudes due to uncertainties in detector performance and absolute calibration are ∼5%. As discussed later, severe crowding may lead to larger overall photometric uncertainties for some objects.

2.2. Astrometry

In order to determine the position of the X-ray source coordinates on the *HST* PC image, we establish a coordinate system based on the *HST* Guide Star Catalog (GSC) reference frame. We begin with the astrometric solution from a digitized Quick V image used to generate the *HST* GSC (Lasker et al. 1990); this frame, obtained directly from ST ScI, contains the astrometric solution in the image header. By centroiding 38 stars in the Quick V image and the corresponding objects in a ground-based CCD image, kindly provided by G. Jacoby, the astrometric reference frame is transferred to the CCD image with an error in the solution of $0\farcs03$.

There are only three stars which are sufficiently isolated to be well-resolved in the ground-based data within the PC field of view, so instead of transferring the solution from the CCD to the PC image, we correct the astrometric information originally provided in the PC header for the average observed offset in position for these three stars (coordinates measured in the PC frame are adjusted by $\Delta\alpha = +0\farcs2$ and $\Delta\delta = +0\farcs5$). The final result is that coordinates may be determined on the PC image to within $\sim0\farcs1$ in the GSC reference frame. However, there may well be some systematic offset, $\sigma \sim 0\farcs5$, from frames based on other reference catalogs (Russell et al. 1990). It should be noted that NGC 6441 is near the edge of the Quick V plate, where systematic errors can be higher.

Figure 1 shows the entire $33'' \times 33''$ F336W PC frame, with our position for the $3''$ radius X-ray error circle overlaid, as well as the $8'' \times 8''$ region around the circle. The X-ray coordinates are derived from *Einstein* HRI observations by Grindlay et al. (1984), who report the 90% confidence error as $3''$.

3. DISCUSSION

3.1. Color-Magnitude Diagram

From all four WFPC2 chips we select ∼17,000 stars for which we have obtained good photometry, and plot their colors and magnitudes in Fig. 2. The scatter in the diagram is largely due to the extreme crowding, even by *HST* standards, in this cluster. There is also doubtless some contamination from field stars for this low Galactic latitude cluster.

We label five objects on the diagram. Star U1 is the most UV-excess object within the X-ray error circle (but not in the cluster!). U7, a star of similar color and magnitude, but well outside

the error circle, is discussed below. Stars B1 and B2 are bluer than the other 245 objects in the error circle (except U1), but seem to be part of a large population of stars which compose a formidable blue tail of the horizontal branch; they are not likely to be related to the X-ray source. We also indicate a rare object, the central star of the globular cluster planetary nebula JaFu 2 (Jacoby & Fullton 1994; Jacoby et al. 1996, 1997). These five objects are discussed further below.

An isochrone from Bertelli et al. (1994) is added to the diagram for comparison. We select a 14 Gyr isochrone with [Fe/H] $= -0.40$, the closest available to the published metallicity for NGC 6441, [Fe/H] $= -0.53$, and apply distance modulus $(m - M)_0 = 15.15$ (Djorgovski 1993). The isochrone U and B magnitudes are converted to m_{336} and m_{439}, where the corrections depend on color; these corrections are estimated using the STSDAS *synphot* package. Finally, we apply reddening to the isochrone, although we find that $\mathrm{E}(B - V) = 0.50$ yields a better fit to the giant branch than the published value $\mathrm{E}(B - V) = 0.42$. However, the uncertainties in the metallicity and filter conversion may easily account for this small shift. Qualitatively, the turnoff and giant branch are modeled well by the isochrone. The known planetary nebula central star lies near the predicted track. The M_{B_0} scale uses a filter correction $B - m_{439} = 0.65$. This correction changes slightly with stellar color; 0.65 is appropriate for F type through the hottest stars, while 0.4 is more appropriate for M0 stars.

Typically a metal-rich cluster such as NGC 6441 has a very red horizontal branch, and so it is surprising that our diagram exhibits a bimodal horizontal branch distribution with such an extensive blue tail. These peculiarities in NGC 6441 were recently discussed in results from a study of several metal-rich globular clusters with *HST* by Rich et al. (1997), where some possible explanations are explored.

NGC 6441 also appears to contain a sizable population of supra-horizontal branch stars, which can be seen in our diagram as well as in Rich et al. (1997). The bluest supra-horizontal branch stars and members of the blue tail may be the principal contributors to the significant but unresolved far-ultraviolet radiation detected with *IUE* by Rich et al. (1993). It is possible that some of these objects are not cluster members, but they do seem to follow the same radial distribution as other cluster stars.

Finally we point out a group of stars even bluer than the extreme blue horizontal branch stars. Two noteworthy members of this population are U1 and JaFu 2, our candidate for the optical counterpart to the X-ray source and a planetary nebula central star, respectively. It remains to be seen if the nature of the other stars in this group is equally exotic.

3.2. Star U1

The UV-excess object which we denote U1 is the only unusual star in the X-ray error circle, and it is therefore an obvious optical counterpart candidate to the globular cluster bursting X-ray source X 1746–370. Figure 3 shows a $3'' \times 3''$ section of both the F336W (U) and F439 (B) images centered on this object. Its $M_{B_0} = 3.0 \pm 0.1$ and $(U - B)_0 = -1.0 \pm 0.1$ may be compared with the typical X-ray burster in the field which has $1 \lesssim M_B \lesssim 5$ and $(U - B) = -1.0$ (van Paradijs 1995). Therefore, not only is the color unusual for a globular cluster star, but the

color and magnitude naturally associate the object with known X-ray burster optical counterparts. Based on our astrometric solution derived from the *HST* GSC, we find coordinates for Star U1 $\alpha(2000) = 17^{\rm h}50^{\rm m}12\overset{\rm s}{.}61$, $\delta(2000) = -37^\circ 03' 06\overset{''}{.}5$. The measurement uncertainty here is negligible compared to the external uncertainties discussed in §2.2.

To explore possible variability of Star U1, we perform aperture photometry on this object and two other nearby objects of similar magnitude and color for all publicly-available *HST* WFPC2 and (pre-COSTAR) FOC observations of this field, and present the results in Table 1. Magnitudes are in the STMAG system for both instruments (therefore permitting intercomparison) and 1σ errors are provided. The considerable reddening correction has not been applied to these magnitudes.

We find clear evidence for ∼30% variability between our two long F336W exposures, taken only 27 min apart. Another short F336W exposure and an FOC F342W image also indicate large variability, although the photometric errors are higher and filter/instrument differences could be responsible for at least part of the apparent discrepancy. Additional evidence for the variability of Star U1 comes from a ∼60% change in m_{439} between our observations and similar observations in the archive taken 1.1 yr later for another program. During the same period, measurements for Stars U7 and B2 (UV and blue stars respectively of similar magnitude) are consistent with no variability within the uncertainties. Such large-amplitude variability for U1 clearly adds considerable confidence that it is indeed the optical counterpart to the low-mass X-ray binary (LMXB).

We note that the X-ray source in NGC 6441 shows variability on timescales of 0.25 hr at amplitudes of ∼15% (Parmar et al. 1989). Assuming our suggested identification is correct, our data indicate $L_X/L_{\rm opt} \sim 10^3$, implying that X-ray fluctuations may be promptly reprocessed into detectable optical variability. Thus the similarity of the observed X-ray and optical variability timescales may not be coincidental.

Despite the unusual color and variability, this identification is not completely secure, however, due to a large number of other UV-excess objects in the cluster, as can be seen in the color-magnitude diagram. In order to estimate the probability that one of these UV-excess stars has fallen in the X-ray error circle by chance, we note that there are 21 objects with $(m_{336} - m_{436}) < 0.0$ in our sample of ∼17,000 stars. Therefore, approximately 10^{-3} of the stars with $m_{439} < 22$ in the cluster have marked UV excess, and as we measure 245 stars within the error circle, we estimate a ∼30% probability that one of the UV-excess population objects would fall by chance in the error circle and might be mistaken for the optical counterpart to the X-ray source. The hazards of these *a posteriori* probability estimates are well-known, so this result must surely be regarded as qualitative rather than quantitative, but the conclusion can also be reached visually from the distribution of UV sources seen in Fig. 4. We find the fraction of ultraviolet-excess stars in the cluster intriguing; it exceeds by $\sim 5\times$ an analogous observation for NGC 1851 by Deutsch et al. (1996a).

Previous workers have noted the marked dispersion in optical luminosities of globular cluster X-ray source counterparts. If U1 is indeed the correct counterpart of the NGC 6441 source, it falls at an optical luminosity similar to that of the NGC 6624 source and intermediate between the sources in NGC 6712 (Anderson et al. 1993) and NGC 1851 (Deutsch et al. 1996a), which are remarkably faint, and that of M 15 AC 211.

We also attempted *HST* spectroscopic observations of U1 with the Faint Object Spectrograph on 1995 July 25, using G160L and G570H gratings, which cover the $1150-2500$ Å and $4600-6800$ Å regions, respectively. The resulting G570H spectrum exhibits only spectral features typical of a late G star. The absolute flux level in the spectrum is about 4× higher than m_{555} for Star U1 in Table 1, but is consistent with the total F555W light in a $0''.5$ diameter circle (the size of the FOS aperture used) centered on this object as measured on a WFPC2 image. We conclude that most of the light in this spectrum is most probably contributed by nearby sources other than Star U1.

The count rate in the G160L spectrum is so low that flux coming from the source cannot be distinguished from an imperfect scattered light subtraction. We set upper limits of order 3×10^{-17} erg cm^{-2} s^{-1} Å^{-1} at 1600 Å and 1×10^{-17} erg cm^{-2} s^{-1} Å^{-1} at 2100 Å. These upper limits are $\sim 3\times$ lower than the measurements obtained from FOC and WFPC2 observations of this source. This may indicate very large amplitude variability, for which of course there is already direct imaging evidence. However, the FOS observations were executed by making a blind offset from a nearby bright star, and it cannot be guaranteed that Star U1 was actually in the aperture for either the G160L or G570H spectra.

3.3. Planetary Nebula JaFu 2

Planetary nebulae are rare in globular clusters; only 4 have been discovered despite considerable effort (Jacoby & Fullton 1994; Jacoby et al. 1997). We measure a magnitude and color for the central star of the planetary nebula JaFu 2 in NGC 6441 (Jacoby & Fullton 1994; Jacoby et al. 1996) which are remarkably similar (Fig. 2) to that of Star U1, our proposed X-ray source optical counterpart. This similarity naturally leads to the possibility that Star U1 may be of comparable nature to JaFu 2, but we believe that the similarity must be coincidental. The planetary nebula star lies quite close to predicted evolutionary tracks, and so its observed properties are consistent with photospheric radiation from a hot, single star. The X-ray source, on the other hand, must be a low-mass binary system containing a neutron star, as X-ray bursts are observed (Li & Clark 1977; Sztajno et al. 1987), and thus its integrated light contains contributions from the compact star, the accretion disk, and the companion. The observed magnitude and colors of Star U1 are consistent with those of bursters in the field. Therefore, despite the unusual nature of both objects, one could have predicted in advance that they could both occupy the same place in the cluster color-magnitude diagram and yet be physically dissimilar.

The natures of two of the UV-excess objects in this cluster have now probably been determined, but the other UV-excess sources remain unexplained. Since they are not luminous in X-rays, they are not similar to Star U1. They may well be planetary nebula central stars, where the surrounding nebula has long since dispersed. However, the cases of Star U1 and JaFu 2 have shown that a similarity in color and magnitude in this diagram does not allow us to infer similarity in nature.

4. THE LUMINOUS GLOBULAR CLUSTER X-RAY SOURCES

Of the 12 luminous LMXBs associated with globular clusters listed in van Paradijs (1995), five now have confirmed or likely optical counterparts (see Deutsch et al. 1996a for references). In order to make a comparison between this sample of globular cluster sources and sources in the field, we have extracted images of each cluster from the *HST* data archive and measured m_{336} and m_{439} for each globular cluster (GC) LMXB optical counterpart; these values are presented in Table 2.

Photometric errors are typically dominated by the ∼5% systematic calibration uncertainties. The uncertainty for Star A in NGC 1851 is higher, 0.1 mag, due to a presumably unrelated companion $0\farcs12$ distant (Deutsch et al. 1996a). Observations of the source in NGC 6624 are complicated by an even closer blend (separation $0\farcs08$, King et al. 1993), completely unresolvable with WFPC2, although easily resolved in an F430W FOC image. We estimate m_{439} for both stars in WFPC2 observations by measuring the total light in the blend and using the flux ratio of the two stars in the F430W FOC image. We then estimate m_{336} for the X-ray source counterpart by subtracting the amount of light expected from the companion, assuming that the latter has the same color as other stars with its m_{439}. The uncertainty in the measurements for this optical counterpart is ∼0.2 mag, comparable to the observed amplitude of variability (Anderson et al. 1997). Indeed, it should be noted that we have obtained only instantaneous magnitudes for all these objects, and the sources are known to be variable in optical or ultraviolet light, except in the case of NGC 1851 (for which there has not yet been an adequate light curve study). Nonetheless, the results are entirely sufficient for our purpose here.

With this homogeneous set of photometric measurements from WFPC2 observations, $\mathrm{E}(B-V)$ and $(\mathrm{m}-\mathrm{M})_0$ values from Djorgovski (1993), and approximate color-dependent conversion relations between STMAG system magnitudes and Johnson U,B (derived using the STSDAS *synphot* package), we calculate B_0, $(U-B)_0$, and M_{B_0}, and list them in columns 7-9 of Table 2. In column 10 we list $\xi = B_0 + 2.5 \log \mathrm{F_X}(\mu\mathrm{Jy})$, the parameter used by van Paradijs & McClintock (1995; hereafter vPM) to characterize the ratio of X-ray to optical flux. We use $\mathrm{F_X}$ values from van Paradijs (1995).

By virtue of their cluster membership, the distance to and foreground reddening of these GC LMXBs can be determined easily, unlike those in the field. This allows a comparison of $(U-B)_0$, M_{B_0}, and ξ for GC sources with those of field LMXBs for which these quantities are known. vPM find for the field sources an average $(U-B)_0 = -0.97 \pm 0.17$ (1σ). All five GC LMXBs measured in Table 2 fall within 1σ of this average.

vPM find an average $(B-V)_0 = -0.09 \pm 0.14$ for the field LMXB, so we assume $M_B = M_V$ in the comparison of absolute magnitudes, as we do not have V data available for several objects. This is likely to be a good assumption, since the $(U-B)_0$ colors show a small dispersion and for Star U1, $(B-V)_0 = 0.0$ (based on the 1995 September 12 data in Table 1). In addition, $(B-V)_0 \sim 0.15$ for AC 211 (Ilovaisky et al. 1993), the reddest object in our table. M_V for bursting sources in the field ranges considerably in vPM, from 1 to 5 with a slight overabundance near $M_V = 1$. Our distribution in M_B for the 5 GC LMXBs, which are all bursting sources, is similar: a range from 1 to 6, but with no overabundance near $M_V = 1$. In fact, there is evidence that the globular clusters sources are on average less luminous: while 70% of field bursters have

$M_V < 2.5$, only one of globular cluster bursters has $M_B < 2.5$. However, with only seven and five sources in each group, respectively, the difference may not be significant.

vPM noted that the bursters they considered (mainly in the field) as a group appear to have systematically lower optical luminosity counterparts than other LMXBs. The data on additional counterparts to the globular cluster bursters discussed here add further evidence for such a difference.

Finally we examine how field and globular cluster LMXBs compare in ξ. The source in M 15 has long been known to be optically overluminous and is already singled out at the bright end of vPM's histogram. The other four GC sources span the entire main distribution of field LMXBs; they do not seem to show a peak near $\xi = 22$ as do the field sources, although of course the sample is small.

In summary, the sample of GC LMXBs optical counterparts obtained thus far appears to be identical in $(U - B)_0$ and similar in M_B to the sample of field bursting sources for which comparison is possible. The uniformity in $(U - B)_0$ might well be expected, as the light at these wavelengths may be dominated by a hot accretion disk, whose spectral slope is rather insensitive to temperature in this regime. However, the GC sources show a very broad distribution in ξ rather than the peak of $\xi = 21.8 \pm 1.0$ (1σ) seen by vPM; in fact, only one of the five cluster sources falls within 1σ of the average of the field LMXBs.

Gnedin & Ostriker (1997) have recently reevaluated destruction rates of globular clusters, and concluded that these timescales are more rapid than previously inferred. A substantial fraction of all initial globular clusters may have been destroyed in a Hubble time, and thus a large fraction of the current stellar population of the bulge may come from clusters. LMXBs are the most luminous stars in globular clusters, and might be useful as a tracer of this hypothesis (see also Grindlay 1985). Indeed, Ostriker (1997) points out that luminous (near-Eddington limited) LMXBs are overabundant in the bulge relative to other galactic locations, just as they are overrepresented in globular clusters. The similarity that we infer here between the optical properties of LMXBs in clusters and those in the bulge is compatible with this interesting concept for the origin of the bulge sources, although clearly the sample size is small. As the bulge LMXBs obviously cannot have been radiating at their current X-ray luminosities for a Hubble time, there are also missing evolutionary parts of this picture.

5. CONCLUSION

We have examined WFPC2 images in NGC 6441 for the optical counterpart to X 1746–370. A color-magnitude diagram of ∼17,000 stars in all 4 chips reveals a bimodal horizontal branch with a long blue tail. Nearly two dozen strongly UV-excess objects are also seen in the CM diagram. Our astrometry, based on the *HST* GSC, places the $3''$ X-ray error circle accurately onto the PC frame. Only one of the UV-excess objects or otherwise unusual stars falls within this error circle. The $M_{B_0} = 3.0$, $(U - B)_0 = -1.0$ for Star U1 is typical of the average properties of bursting X-ray sources in the field. We detect a ∼30% variability between our F336W images separated by 0.5 hr, and a ∼60% variability between our F439W frames and F439W images taken 1.1 yr later. The color and variability combine to make U1 a very strong candidate for the optical counterpart.

We do note that there is a sizable population of UV-excess stars in the cluster and calculate a $\sim$30% probability that a member of this population would have fallen in the X-ray error circle by chance. An FOS spectrum ostensibly of Star U1 detects no significant UV flux with an upper limit 3$\times$ lower than fluxes obtained from imaging, indicating either very high UV variability or target acquisition failure. We plan *HST* STIS time-resolved spectroscopy to confirm the candidate and lead to better understanding the nature of this object.

With five cluster optical counterparts now known, we present a homogeneous set of *HST* m_{336} and m_{439} measurements, and calculate M_{B_0}, $(U-B)_0$, and ξ for each object. A comparison with sources in the field for which these values are determined show remarkably good agreement in $(U-B)_0$, a similarity in M_{B_0} for bursters in the field and in globular clusters (but with burster counterparts perhaps less luminous than other field LMXBs), and apparently larger dispersion in ξ for the globular cluster X-ray sources. One-quarter century after their discovery in X-rays, enough optical counterparts are finally known (largely thanks to *HST*) that an initial study of the ensemble optical properties of this interesting class of object is now possible.

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REFERENCES

Anderson, S. F., Margon, B., Deutsch, E. W., & Downes, R. A. 1993, AJ, 106, 1049

Anderson, S. F., Margon, B., Deutsch, E. W., Downes, R. A., & Allen, R. G. 1997, ApJ, 482, L69

Bailyn, C. D., Grindlay, J. E., Cohn, H., & Lugger, P. M. 1988, ApJ, 331, 303

Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F. & Nasi, E. 1994, A&AS, 106, 275

Clark, G. W. 1975, ApJ, 199, L143

Deutsch, E. W., Anderson, S. F., Margon, B., & Downes, R. A. 1996a, ApJ, 472, L97

————. 1996b, BAAS, 28, 1328

Djorgovski, S. 1993, in ASP Conf. Ser. 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco: ASP), 373

Gnedin, O. Y., & Ostriker, J. P. 1997, ApJ, 474, 223

Grindlay, J. E. 1985, in IAU Symp. 113, Dynamics of Star Clusters, ed. J. Goodman & P. Hut (Dordrecht: Kluwer), 43

Grindlay, J. E., Hertz, P., Steiner, J. E., Murray, S. S., & Lightman, A. P. 1984, ApJ, 282, L13

Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995a, PASP, 107, 1065

Holtzman, J. A., et al. 1995b, PASP, 107, 156

Ilovaisky, S. A., Aurière, M., Koch-Miramond, L., Chevalier, C., Cordoni, J.-P., & Crowe, R. A. 1993, A&A, 270, 139

Jacoby, G. H., & Fullton, L. 1994, BAAS, 26, 1384

Jacoby, G. H., Morse, J., Fullton, L., Kwitter, K., & Henry, R. B. C. 1996, BAAS, 29, 1353

Jacoby, G. H., Morse, J., Fullton, L. K., Kwitter, K. B., & Henry, R. B. C. 1997, in preparation

Katz, J. I. 1975, Nature, 253, 698

King, I. R. et al. 1993, ApJ, 413, L117

Landsman, W. B. 1993, in ASP Conf. Ser. 52, Astronomical Data Analysis Software and Systems II, ed. R. J. Hanisch, R. J. V. Bissenden, & J. Barnes (San Francisco: ASP), 256

Lasker, B. M., Sturch, C. R., McLean, B. J., Russell, J. L., Jenkner, H., & Shara, M. M. 1990, AJ, 99, 2019

Li, F., & Clark, G. 1977, IAUC 3095

Ostriker, J. P. 1997, paper delivered to Ostriker Festschrift, Princeton NJ, May 1997

Parmar, A. M., Stella, L., & Giommi, P. 1989, A&A, 222, 96

Peterson, C. J. 1993, in ASP Conf. Ser. 50, Structure and Dynamics of Globular Clusters, ed. S. G. Djorgovski & G. Meylan (San Francisco: ASP), 337

Rich, R., M., et al. 1997, ApJ, 484, L25

Rich, R. M., Minniti, D., & Liebert, J. 1993, ApJ, 406, 489

Russell, J. L., Lasker, B. M., McLean, B. J., Sturch, C. R., & Jenkner H. 1990, AJ, 99, 2059

Sansom, A. E., Dotani, T., Asai, K. & Lehto, H. J. 1993, MNRAS, 262, 429

Schechter, P., Mateo, M., & Saha, A. 1993, PASP, 105, 1342

Sztajno, M., Fujimoto, M. Y., van Paradijs, J., Vacca, W. D., Lewin, W. H. G., Penninx, W., & Trümper, J. 1987, MNRAS, 226, 39

van Paradijs, J. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ.), 536

van Paradijs, J., & McClintock, J. E. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ.), 58 (vPM)

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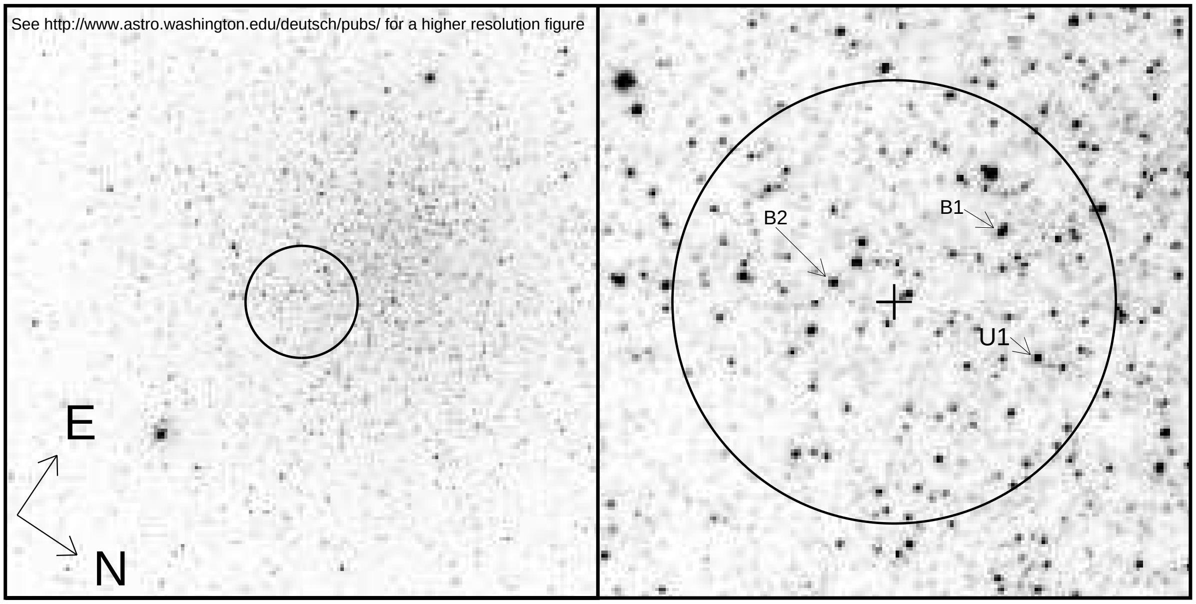

Fig. 1.— *Left panel*: $33'' \times 33''$ *HST* WFPC2 PC image of the core of NGC 6441 with the F336W (U) filter. A $3''$ radius error circle has been drawn about the *Einstein* HRI coordinates for the luminous bursting X-ray source X 1746–370. *Right panel*: $8'' \times 8''$ section of the same image, centered at our optical position for the X-ray coordinates (indicated with a cross). Ultraviolet-excess object U1, which we offer as a likely optical-counterpart candidate, is indicated along with two blue stars (labeled B1 and B2) which also fall within the error circle.

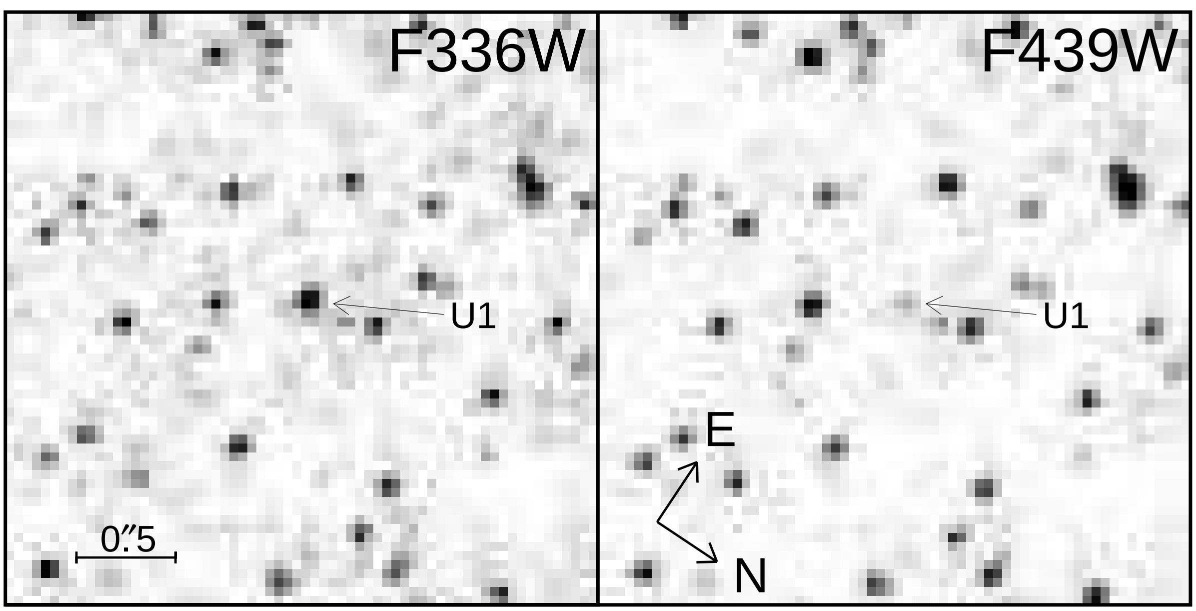

Fig. 3.— $3'' \times 3''$ sections of the F336W (U) and F439W (B) images centered on Star U1, which we select as a candidate optical counterpart due to significant UV excess and variability. These images were obtained on 1994 August 8 (cf. Table 1).

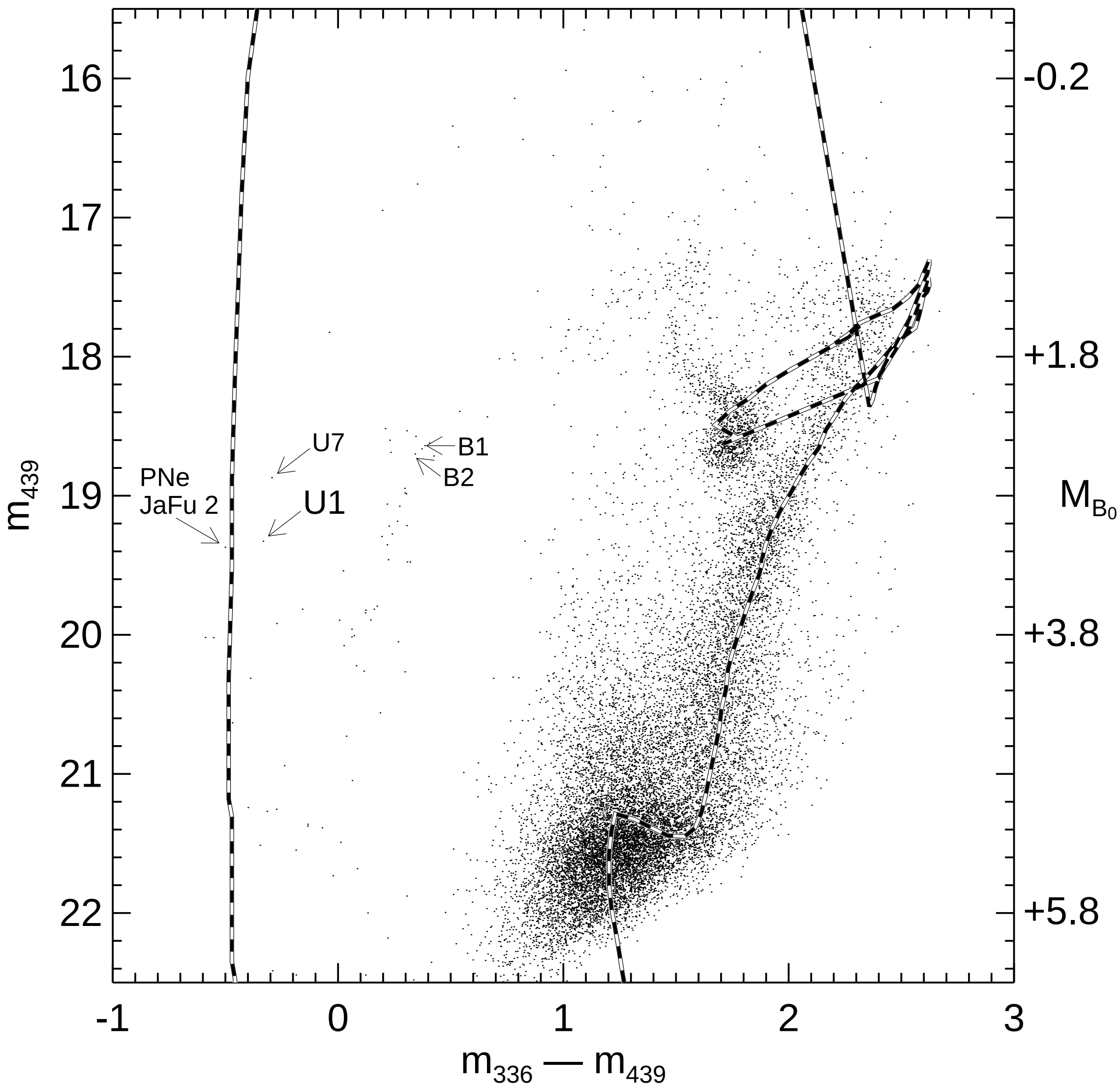

Fig. 2.— Color-magnitude diagram for ∼17,000 stars on all 4 chips of the WFPC2 exposures. Magnitudes are in the STMAG system; see text for details. Objects which are discussed in the text are labeled: Star U1, which we select as a candidate optical counterpart due to significant UV excess and variability; the central star of cluster-member planetary nebula JaFu 2; blue Stars B1 and B2, which also fall within the X-ray error circle but are probably not related to the X-ray source; Star U7, one of several objects with similar color and magnitude to U1. Note the surprisingly well-populated branch of extreme blue horizontal branch stars typified by B1 and B2. An isochrone from Bertelli et al. (1994) is also overlaid; see text for more details.

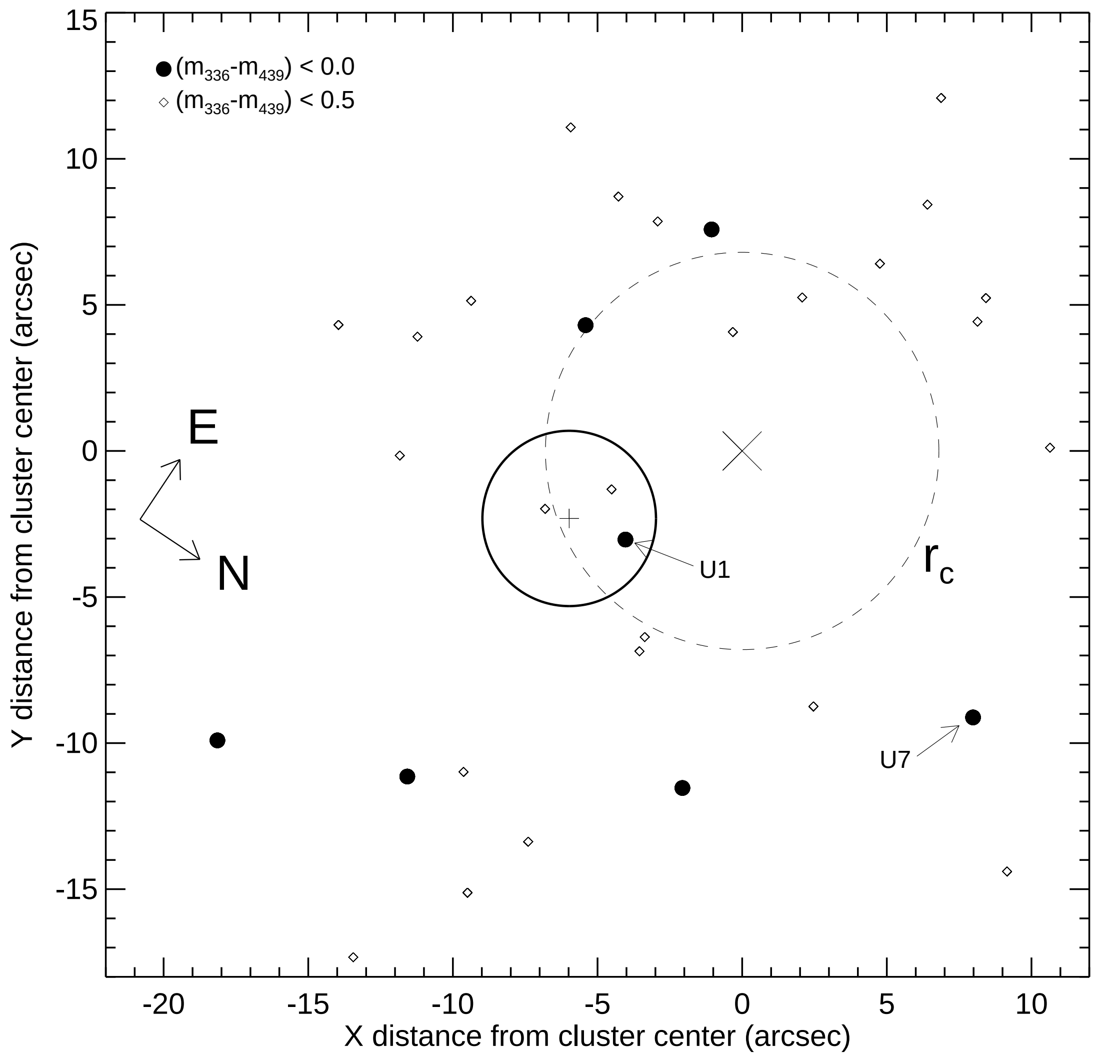

Fig. 4.— The locations of the UV stars $(m_{336} - m_{436}) < 0.0$ and blue stars $(m_{336} - m_{436}) < 0.5$ on the PC image (compare to Fig. 1). The *Einstein* X-ray error position (cross) and $3''$ radius error circle are shown (solid line). The cluster center and core radius are shown with a $\times$ and dashed-line circle, respectively. Stars U1, B1, and B2 are within the error circle, but a considerable population of both UV and blue stars can be seen throughout the entire PC image. Note that the bluest objects do not appear to have a marked central concentration.

Table 1. Photometry for selected objects in current observations and archival *HST* data of NGC 6441

Filter (Camera)	Obs Date	Start Time	Exp. Time (s)	Star U1 (mag)	(err)	Star U7 (mag)	(err)	Star B2 (mag)	(err)
F140W (FOC)	93/09/28	03:29	996	19.20	0.24	19.03	0.15	> 20.8	0.8
F210M (FOC)	93/09/28	04:51	996	20.22	0.36	19.56	0.18	20.01	0.25
F218W (WFPC2)	95/09/12	06:13	500	19.73	0.18	19.16	0.15	20.19	0.26
		06:24	1000	19.94	0.15	19.44	0.11	20.14	0.15
F336W (WFPC2)	94/08/08	13:37	50	19.12	0.07	18.61	0.05	19.09	0.07
		13:40	500	18.87	0.02	18.62	0.01	19.07	0.02
		14:07	500	19.19	0.03	18.65	0.02	19.08	0.02
F342W (FOC)	93/09/28	05:13	496	18.81	0.09	18.79	0.04	19.07	0.10
F439W (WFPC2)	94/08/08	13:52	50	19.19	0.10	18.91	0.05	18.67	0.05
		13:55	500	19.28	0.04	18.87	0.02	18.65	0.03
	95/09/12	06:01	50	18.77	0.06	18.91	0.06	18.57	0.06
		06:04	160	18.80	0.04	18.78	0.04	18.61	0.04
		06:08	160	18.75	0.04	18.80	0.04	18.63	0.04
F555W (WFPC2)	95/09/12	05:55	14	18.94	0.06	19.25	0.06	18.95	0.06
		05:57	50	18.95	0.04	19.26	0.06	18.94	0.07

Table 2. Photometry for globular cluster LMXB optical counterparts from *HST* data

Optical Counterpart	$(m-M)_0$[a]	E$(B-V)$[a]	[Fe/H][a]	m_{439}[b]	$(m_{336}-m_{439})$[b]	B_0	$(U-B)_0$	M_{B_0}	ξ[c]
NGC 1851 Star A	15.43	0.02	-1.29	20.46	-0.73	21.03	-0.98	5.60	22.97
NGC 6441 Star U1	15.15	0.42	-0.53	19.30	-0.30	18.18	-1.06	3.03	21.94
NGC 6624 King Star	14.54	0.28	-0.37	17.99	-0.37	17.46	-0.98	2.92	23.46
NGC 6712 Star S	14.16	0.46	-1.01	19.88	-0.19	18.58	-1.02	4.42	20.70
M15 AC 211	15.11	0.05	-2.17	15.49	-0.45	15.91	-0.81	0.80	17.86

[a] Cluster properties from Djorgovski (1993) and Peterson (1993)

[b] Photometric uncertainties are discussed in the text, but most of these objects are known to be variable and the rest are likely to be as well.

[c] Optical photometry from this work; F_X from van Paradijs (1995)